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FLIGHT-INFORMATIONAL SENSORS, DISPLAY, AND SPACE CONTROL OF THE X-15 AIRPLANE FOR ATMOSPHERIC AND NEAR-SPACE FLIGHT MISSIONS

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FLIGHT-INFORMATIONAL SENSORS, DISPLAY, AND SPACE CONTROL OF THE
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SUMMARY

Various flight-informational sensors and some nonconventional pilot-display quantities have been evaluated and used on the X-15 airplane during the expansion of the flight envelope to high altitudes and hypersonic speeds and in the accomplishment of the programmed research missions. Also, flight-guidance information has been provided by the ground-control monitoring stations.

Several of the systems evaluated appear to be satisfactory for providing research and pilot-display information relative to airspeed, altitude, dynamic pressure, flow-direction angles, and vehicle attitude. Other systems need additional refinement of calibration and some onboard computational equipment if required for the pilot display.

In general, use of a nose-boom installation on aircraft designed for speeds up to a Mach number of about 3 is recommended as the prime air-sensing source and for flow-direction measurements. For higher speeds and their associated altitudes, use of a ball nose or similar sensor having a high-temperature capability, in conjunction with an accurately calibrated static source which is independent of all configurational and rotational effects, appears to be warranted. The inertial system tested provided satisfactory attitude information for long periods; however, the accuracy of the altitude output deteriorated because of the short-term reliability of the system. A stagnation-temperature sensor appears to be a promising source for velocity information at supersonic and hypersonic speeds but requires further development.

Although the cockpit display used in the X-15 program can be improved, it has generally enabled precise attainment of goals for specific missions, particularly with the aid of special displays and backup methods devised in preflight simulation planning. Even though the flight-guidance information provided to the pilot by ground-monitoring personnel is not essential for the accomplishment of every flight, it has contributed significantly to the success of the flight program.

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INTRODUCTION

The X-15 rocket-powered airplane (fig. 1) was developed as an advanced research tool to provide research data and operational experience on manned vehicles operating both inside and outside of the earth's atmosphere, particularly at hypersonic speeds. To accomplish these objectives and to provide the necessary flight-guidance information to the pilot to enable him to effectively perform a variety of flight missions, various flight-informational sensors and some nonconventional pilot-display quantities have been evaluated and used on the X-15. In addition, space-positioning and other guidance information have been provided by the ground-control monitoring stations. These techniques have contributed to the achievement of a Mach number of 6.04 and an altitude of 314,750 feet.

Because of the need for reliable flight-guidance information for existing and future aerospace vehicles, the sensors and techniques developed in the X-15 program are considered to be of general interest. Also, the systems and techniques investigated can contribute to the design and utilization of equipment and procedures for efficient flight-profile programing at both low and high speeds.

This paper presents pertinent information obtained during the X-15 program and discusses its use by the pilot in performing a variety of atmospheric and near-space flight missions.

SYMBOLS

C_N	normal-force coefficient
h	altitude, ft
Δh	pressure-altitude error (true altitude minus indicated altitude), ft
$K = \frac{q}{p_t}$	
M	free-stream Mach number
M'	indicated Mach number
p	total or static pressure, psf
q	free-stream dynamic pressure, psf
Δq	difference between true and indicated dynamic pressure, psf
t	time, sec

V	velocity, ft/sec
α	angle of attack, deg
$\Delta\alpha$	angle-of-attack error, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
θ	airplane pitch attitude, deg

Subscripts:

b	base area
bn	ball nose
p	pilot's pitot probe
t	total or stagnation
∞	ambient
70	orifice at 70° location of ball nose

DESCRIPTION OF FLIGHT SENSORS AND SYSTEMS

Although ground monitors are provided with radar velocity, altitude, position and heading information, as well as telemetered quantities, during each X-15 flight, development of satisfactory onboard sensors and displays for flight-guidance information to the pilot is considered mandatory.

In the early stages of the X-15 flight program, a standard NACA type of pitot-static tube and free-floating vanes mounted on a nose boom (fig. 2) were used to provide total pressure, static pressure, and flow-direction measurements. Similar sensors had been used on previous NACA research aircraft. Almost simultaneously with the first flights of the X-15, flight development of an inertial flight-data system was initiated to provide recording and pilot displays of velocity, altitude, and three-axes attitude angles. Development of the inertial system was undertaken in view of anticipated nose-boom limitations associated with low-pressure measurements at high altitudes and with hypersonic heating effects.

With the expansion of the X-15 flight envelope beyond a Mach number of 3 and altitudes above 100,000 feet, the problems of high temperature and low pressure necessitated flight development and use of an advanced flow-direction sensor or "ball-nose sensor" to replace the nose-boom angle-of-attack and angle-of-sideslip information. The total pressure sensed by the ball nose and the pressure sensed at a static source at the 70° location above the total-pressure

port have also been used to determine the suitability of these pressure sources for display and recording of altitude and speed.

As a backup for the ball-nose sensor and the inertial system, a pitot probe was located ahead of the cockpit canopy. This probe, along with selected side-fuselage static sources, was connected to the pilot's instruments for use during the subsonic landing portion of each mission. Other sources of velocity and static-pressure data have also been investigated and are still being studied.

Nose-Boom Sensor

The pitot-static tube (figs. 2 and 3) mounted on a nose boom ahead of the fuselage was a natural selection for the early X-15 flights, on the basis of extensive wind-tunnel studies and previous use on NACA research aircraft, to provide airspeed, altitude, and angle-of-attack and angle-of-sideslip data. The pitot probe used on the X-15 was cambered to give a 10° slant on the end, thus providing a stagnation-pressure head which is relatively insensitive to angles of attack between -13° and 32° (less than 1-percent error in total pressure). The static orifices were located 63 inches forward of the tip of the aircraft nose (figs. 2 and 3) and 9 pitot-tube diameters rearward of the end of the nose boom to minimize interference effects.

Free-swiveling, mass-balanced vanes mounted on the nose boom provided angular position data by means of a synchro-transmitter attached to the inboard end of each vane shaft. To improve the symmetry of the flow field for the angle-of-sideslip vane, a dummy shaft was mounted opposite the angle-of-attack-vane strut.

Data obtained from this sensory system were recorded onboard and presented in the pilot's display. The flow-direction data were also telemetered to the ground-monitoring station for real-time monitoring.

Pilot's Pitot Probe

Since the removal of the nose boom for speeds above a Mach number of 3, the stagnation-pressure source for the pilot's subsonic airspeed system has been the pitot probe (figs. 2 and 4). This probe is located directly ahead of the canopy, 70 inches rearward of the fuselage nose.

Static-Pressure Sources

A flush static system consisting of two manifolded orifices, one on each side of the fuselage, 50 inches rearward of the fuselage nose and 2 inches above the centerline (figs. 2 and 4) was provided for pilot use on landings after the nose boom was replaced by the ball nose. These orifices were selected to provide minimum errors over the speed and angle-of-attack ranges experienced during landings.

Because of the sensitivity to angle-of-attack effects of the fuselage-located static-pressure orifices, particularly at supersonic speeds, other possible locations on the X-15 were studied. Two areas being investigated (fig. 4) are a source on the base area of the upper vertical fin and a source on the blunt trailing edge of the wing flap.

Hypersonic Flow-Direction Sensor

A photograph of the high-temperature flow-direction sensor installed on the nose of the X-15 airplane is shown in figure 5. This sensor consists of a 6 1/2-inch-diameter actuated sphere partly housed within a 16 3/4-inch-long truncated cone. The internal temperature of the sensor is controlled by a temperature-demand system that utilizes liquid nitrogen as a coolant.

Operationally, the sensor is a null-seeking, hydraulically actuated, electronically controlled servomechanism (fig. 6). The differential pressure between opposing sphere-surface orifices (two in the pitch plane and two in the yaw plane) is measured, and the resulting unbalance signal causes the hydraulic actuators to position the sphere to balance this differential pressure. The sphere position is a direct indication of the angle of attack and the angle of sideslip. This position is electronically detected and transmitted to the on-board indicating and recording instruments and also telemetered to the ground-monitoring station. Because the dynamic pressure can vary from less than 1 psf to 2,500 psf, system stability and accuracy are maintained by a gain adjustment in the servo loop. This adjustment is provided by measuring the pressure difference between the total-pressure orifice and one of the angle-sensing orifices and was designed on the basis of the anticipated rate of change of dynamic pressure during an entry. Based on ground tests, the angular accuracy of the sensor is within $\pm 0.25^\circ$ for dynamic pressures above 10 psf.

In addition to use in the servo gain network, the sensor total pressure (fig. 6) has been used occasionally for onboard presentation to the pilot of airspeed and "apparent" dynamic pressure and also for onboard recording of these quantities.

In a recent study of static sources which could be used over a wide speed range and which would be essentially devoid of angle-of-attack or angle-of-sideslip effects, an orifice was installed at the 70° location above the total-pressure port. Pressure measurements from this source have been recorded.

Inertial Data System

The X-15 inertial flight-data system is basically an earth-slaved, Schuler tuned system aligned in azimuth to an equivalent guidance equator that is coincident with the centerline of the X-15 radar range. Vehicle attitudes, velocities, and height are determined by the inertial system with respect to the X-15 range coordinates. They are presented on the pilot's display and recorded by onboard instrumentation.

Major system components on the X-15 include the computer, stabilizer, and pilot's display (fig. 7). The stabilizer contains a four-gimbal system to provide complete attitude freedom in all axes and utilizes three force rebalancing accelerometers and three single-degree-of-freedom gyroscopes. The computer is a direct-current analog type which converts stabilizer information into velocity and position data and includes necessary acceleration corrections. It also provides processing of erection and alinement information.

At the time this system was selected, an all-inertial operation from take-off to landing would have required a system too heavy and too large to be practical for the X-15; therefore, an inertial data system with radar-damped, in-flight alinement techniques prior to launch was chosen. This system was designed to provide a post-launch capability of 300 seconds of fairly accurate velocity and height data and 20 minutes of attitude data (table I). Because of the types and profiles of the X-15 missions, it was initially assumed, and has since been demonstrated, that within 300 seconds after launch from the B-52, the X-15 pressure instruments are adequate for vehicle height- and velocity-control data. Erection and alinement of the stabilizer requires extensive and accurate reference equipment aboard the B-52 carrier aircraft (fig. 7). An AN/APN-81 Doppler radar is used as a horizontal-velocity reference for alinement to the vertical during captive flight, and an N-1 compass is used for heading reference during the straight and level portions of the carried flight.

Position data for initial conditions and confidence checks are provided by ground radar and a B-52 pressure altimeter. The B-52 control panel provides monitoring of mode control and system performance and also processes reference information for use in the computer.

Stagnation-Temperature Probe

A photo of the total-temperature probe tested on the X-15 for use as a velocity-indicator source is shown in figure 8. The thermocouple probe was installed on the leading edge of the left wing at the tip, and the output voltage was recorded on an oscillograph in the instrument bay. The error in temperature measurement specified by the manufacturer was less than 2 percent for total pressures greater than 600 psf and total temperatures less than 2,400° F. Most data flights made with the probe were within these limits. The accuracy decreases gradually with decreasing total pressure.

FLIGHT-DATA MEASUREMENTS

Airspeed-Altitude Data

The airspeed-altitude data obtained by the pressure, inertial, and temperature systems investigated are presented in figures 9 to 14.

Pressure-measuring systems.- The accuracy of pressure sources in determining either speed or altitude, or both, for a vehicle in subsonic or supersonic flight

depends upon the determination of accurate relations of measured to free-stream conditions. With radar values used as a baseline, figure 9 illustrates the degree of error in Mach number and altitude for the nose-boom pressure system and the pressure system composed of the ball-nose total-pressure source and fuselage static-pressure source. Although the ball-nose total-pressure measurements are considered to be satisfactory, based on previous studies, the curves for the combined ball-nose total and fuselage static system are not accurate calibration curves. They are included to illustrate the trends with change in angle of attack that result from the location of the static-pressure orifices. These position errors in static-pressure measurements are reflected as errors in Mach number and altitude, which increase rapidly with increase in Mach number (fig. 9). In contrast, the nose-boom static pressure was insensitive to angle of attack up to the maximum experienced; however, because of position error, the Mach number and pressure-altitude errors increased slightly with Mach number. At $M = 3.31$, the highest Mach number attained with the nose boom, the absolute errors were 0.18 in Mach number and 2,200 feet in pressure altitude. At the same Mach number, the corresponding errors in Mach number and altitude for the ball-nose total and fuselage static system were 0.88 and 12,400 feet, respectively, for $\alpha = 0^\circ$, and 0.50 and 6,300 feet for $\alpha = 12^\circ$. It should be noted that these errors are applicable to direct-reading cockpit instruments and are considered excessive for the combined ball-nose total and fuselage static system. However, by using an onboard computer, improved accuracy for a cockpit display can be attained with either system.

The ratio of total pressures recorded from the pilot's pitot probe and the ball-nose total source as a function of Mach number is shown in figure 10. This figure illustrates the degree of error due to angle-of-attack changes inherent in the pilot's pitot probe ahead of the canopy. At subsonic speeds, no significant differences could be observed that are attributable to angle-of-attack effects. At supersonic speeds, the pressure ratio is considerably affected by angle of attack above $M \approx 1.8$, because of local-flow characteristics behind the aircraft bow wave. This system is used in the pilot's cockpit display primarily for the low-speed and landing regime; however, at supersonic speeds, the standard airspeed indicator spins rapidly for even small angle-of-attack changes.

Previous wind-tunnel and flight studies indicated the impracticability of locating a static source devoid of position error over the entire supersonic range. However, the sensitivity to angle of attack of fuselage-located static-pressure sources at supersonic speeds generated a study of other possible locations on the X-15. Two other sources, on aircraft-component base areas, show promise supersonically and are being investigated because of their apparent insensitivity to angle of attack. Data obtained for these locations up to angles of attack of 20° are shown in figure 11, which presents the difference in base and ambient pressures divided by dynamic pressure as a function of Mach number. The data for the static source on the base of the upper vertical fin, which were obtained with speed brakes open and closed, show effects of aircraft engine power and, therefore, appear to be limited in application. Data recorded on the trailing edge of the X-15 flap reduced the scatter substantially. The sensitivity to angle of attack was reduced greatly, and the effects of power were completely eliminated. The location of pressure sensors in this area offers a good possibility of refined calibration and measurement of static pressure on the X-15. However, it should be realized that use of these sources for onboard

presentation to the pilot would require some computational equipment to convert the measured data to an ambient pressure.

The unique characteristics of the ball nose in maintaining a constant alignment with the airflow vector provide an excellent opportunity for making pressure measurements on the sphere, since the pressure distribution on the spherical surface is unaffected by flow angularity and is defined by only two parameters — Mach number and dynamic pressure. Accordingly, one of the ball-nose sensors has been modified by incorporating a 70° pressure-sensing port. Some preliminary calibration results are presented in figure 12. The altitude error using the 70° port increases significantly with Mach number above $M = 1$, and the position error is larger than for the nose boom; thus, the error in Mach number, using this 70° port and the ball-nose total pressure, is also larger than that for the nose boom. Although it is expected that the scatter shown by these data can be appreciably reduced, the larger position error of this 70° port installation would present the pilot with greater error in a direct-reading cockpit display than would the nose boom. However, by using an onboard computer in conjunction with the ball-nose total pressure and the 70° port pressure, it appears that a suitable flight-guidance display can be presented for Mach numbers below about 3. At higher Mach numbers, the usefulness of this system appears to be limited because of deterioration in accuracy.

Inertial flight-data system.— Figure 13 shows a direct comparison between inertial velocity and altitude data and comparable radar data for about two-thirds of the normal flight time of a representative flight. In general, good agreement is exhibited for both quantities over most of the time period shown; however, the inertial altitude data show a typical divergence from true altitude during the second half of the flight. This altitude divergence normally starts at launch as a result of erroneous initial conditions, but is not particularly noticeable or objectionable until the later flight phases after peak velocity and altitude have been attained. As previously discussed, the inertial system was designed to provide reasonably accurate values of velocity and altitude for the first 300 seconds of flight. Although system performance has tended to improve with flight-development procedures, the data output is not considered to be sufficiently reliable as a sole source of research information. For flight-control purposes, the velocity output appears to be generally adequate; however, the altitude readouts are obviously usable only for the initial flight period.

Stagnation-temperature velocity sensor.— Figure 14 shows a comparison of the velocity calculated by using the stagnation-temperature probe and the faired radar velocity for a flight to a peak velocity of 6,005 ft/sec. Although the total-temperature-sensor velocity agreed with the radar or true velocity during the powered acceleration period, it was generally about 150 ft/sec higher than radar over most of the supersonic glide-deceleration period of flight. Studies with this sensor are continuing. The sensor appears to offer promise for pilot-presentation displays, particularly at the higher Mach numbers where pressure-sensing systems are subject to appreciable position errors.

Flow-Direction Data

To assess the operating characteristics of the vane-boom or ball-nose flow-direction (α and β) sensors, a comparison was made of the variation of airplane normal-force coefficient with angle of attack measured individually with both sensors (fig. 15). Wind-tunnel test results for the X-15 model are also presented in this figure.

In wind-tunnel vane-boom calibration studies at the NASA Langley Research Center, the angles of attack indicated by the vane were somewhat high, particularly at Mach numbers from 0.9 to 1.47. This error is attributed to an upwash effect caused by the nose boom extending ahead of the vane. At Mach numbers below 0.9 and greater than 1.47, the error amounted to about 1° in 20° ; however, the error was essentially zero for angles of attack less than 10° at supersonic speeds. These studies also indicated that the errors of the angle-of-sideslip vane ranged from 0° to 1.5° for sideslip angles up to $\pm 10^\circ$ and varied in magnitude and sign with Mach number. Inasmuch as the vane-boom configuration used in the flight studies was identical to that used in the wind-tunnel calibration studies, it is assumed that the vane-boom flow-direction flight results are correspondingly high.

The agreement in the flight data shown in figure 15 for the two sensors at the lowest supersonic speed ($M = 2.0$) is good. At $M = 0.9$, the apparently excessively high values of angle of attack obtained with the ball-nose sensor are attributed to the subsonic upflow effect at the nose of the fuselage. Upwash corrections applied to the flight data (on the basis of ball-nose-sensor wind-tunnel tests) would provide good agreement of the ball-nose data with the vane-boom data. At all speeds shown, a slight scatter is exhibited by the flight data which is attributed to the oscillatory nature of the flight maneuvers; however, both the vane boom and the ball-nose sensors provided repeatable data with little spread. In general, the agreement between the flight data and the wind-tunnel data is good, despite the fact that the wind-tunnel results were interpolated from data obtained at several facilities.

Although the nose boom has not been used in flight on the X-15 to extremely low dynamic pressures (below 9 psf), the ball-nose sensor has been tested in this flight range. The results have been fairly accurate, in spite of the degradation in performance with decrease in dynamic pressure. In figure 16, flight data are compared with the analytical projection of the sensor accuracy in the low-dynamic-pressure region. The accuracy of the flight data shown was obtained by comparing the angle of attack as measured by the sensor (α_{sensor}) with the angle of attack computed by using pitch attitude obtained from the inertial platform (θ_{inertial}) in nearly wings-level flight and the flight-path angle as derived from radar information (γ_{radar}). It should be noted that the accuracy of the flight-path-angle determination is fairly limited. As shown in the figure, the maximum difference between the flight and analytical projections of sensor accuracy is less than $3/4^\circ$ at a dynamic pressure of 3.5 psf. For dynamic pressures below 1 psf, the sensor output is essentially unusable.

The repeatability and accuracy of the angles of sideslip obtained from the ball-nose sensor are essentially the same as specified for the angle-of-attack data and are considered adequate, even to extremely low dynamic pressures.

Inertial-System Attitude Data

An indication of the suitability of the attitude-angle information provided by the inertial system is shown in figure 17. The pitch attitude indicated by the inertial system at engine burnout of the X-15 is plotted as the ordinate, and the pitch attitude obtained by the sum of the flight-path angle γ derived from radar information and the measured angle of attack α from the ball-nose sensor is plotted as the abscissa. Although this comparison shows only moderately good agreement in the low range for the pitch-attitude angles obtained by the two techniques discussed, it should be noted that the accuracy of the flight-path-angle determination in the flatter trajectories is fairly limited. In general, the pitch-attitude data produced by the inertial system appear to be accurate and reliable over the entire range evaluated.

Similarly reliable flight results were provided by the inertial system for bank and heading information recorded by onboard instrumentation. Furthermore, post-flight attitude readings obtained immediately after touchdown indicated that the inertial system provided fairly accurate attitude data throughout the flight, including the landing.

X-15 COCKPIT DISPLAY

Despite the multimission flight capability and large flight envelope of the X-15, its overall cockpit display is essentially conventional, inasmuch as the operating level of many of the aircraft and engine systems is shown in a standard form.

Some of the salient items used for pilot presentation in the X-15 are shown in the main-panel display of figure 18. The panel area shown above the heavy white lines contains the primary flight quantities; the display quantities below the white lines represent several important aircraft and engine systems. The prime flight indicators include: a three-axis attitude ball (which includes vernier indications of α , β , and θ), a normal-acceleration indicator, an angle-of-attack indicator, a roll-rate indicator, a stopwatch for rocket-engine operation, pressure altitude and airspeed indicators, and inertial values of altitude, velocity, and rate of climb. In addition, the area directly above the three-axis attitude ball has been used at various times to display and evaluate "new" quantities or quantities desired for specific missions, such as angle of sideslip (gross indication), dynamic pressure, or flight-path velocity indicated by a stagnation-temperature probe.

In almost all instances, circular scales that were uniformly graduated and easily read by the pilot were used. The angle-of-attack indicator was, of course, operated by electrical signals provided initially by the nose-boom vane and then by the ball-nose sensor. The normal-acceleration indication was provided by a self-contained accelerometer unit positioned behind the display panel. The dynamic-pressure indication, although slightly in error because ambient pressure was neglected, was provided by a factored value of the total pressure from the ball-nose sensor, but was limited in use to the range above $M \approx 2.5$. (The dynamic-pressure display is discussed in more detail later.) The stopwatch used

for timing rocket-engine operation was started by actuation of the engine main propellant valve. The inertial velocity, height, and rate-of-climb display are operated from the output of the inertial-system computer. The pressure-altitude and airspeed display currently uses the stagnation pressure from the pilot's pitot probe and the static pressure sensed at the side-fuselage ports; however, this display initially used the nose-boom total and static pressures.

Perhaps the most important cockpit instrument in the X-15 is the three-axis attitude ball (fig. 19). In addition to the aircraft-attitude presentation provided by the ball indicator, a pitch null vernier is located on the left side of the indicator, and crossbars are incorporated within the face of the attitude indicator to provide vernier indications of angle of attack (about a preselected null position) and of angle of sideslip. As previously discussed, attitude information is provided by the inertial data system, and angles of attack and sideslip are provided by the nose-boom vanes or the hypersonic flow-direction sensor.

As a result of the increased accuracy desired in attaining specific conditions of dynamic pressure during various X-15 flights, attention was given to presenting this information to the pilot on the basis of ball-nose total pressures. As shown in the upper portion of figure 20, the ratio of free-stream dynamic pressure to total pressure is an explicit function of Mach number. Above a Mach number of 2.5 the ratio approaches a constant value. The theoretical errors in dynamic pressure for selected values of the ratio q/p_t (or K) of 0.526 and 0.540 are shown in the lower portion of the figure. Using the value of 0.526, the values of indicated dynamic pressure will be 5 percent high at $M = 2.1$ and 2.5 percent low at $M = 6$. (This value of the ratio was used in providing a display to the pilot.) The lower portion of figure 21 shows the error between indicated and radar-calculated dynamic pressures for an actual X-15 heating flight (upper portion of figure). During the critical or usable part of the flight ($M > 2.5$), the pilot was given dynamic pressure generally within 2 percent.

GROUND-BASED GUIDANCE EQUIPMENT

Although the pilot of the X-15 is in complete control of his flight, the ground-monitoring station performs a number of important functions in supporting the flight operation. The primary functions of the ground-control station are to:

- Monitor operation of the subsystems during the flight and advise the pilot of any discrepancies.

- Position the B-52 airplane over the desired launch point at the desired time by advising the B-52 pilot of course corrections and countdown-time corrections prior to launch.

Time the engine operation as a backup for the onboard stopwatch.

Advise the X-15 pilot of heading corrections, radar altitudes, and position during the flight.

Monitor and evaluate stability and control parameters.

Monitor the X-15 pilot's physiological environment.

Provide the X-15 pilot with energy-management assistance.

Direct air search and rescue operation in an emergency.

A view of the X-15 ground-control station at the NASA Flight Research Center is shown in figure 22. This station is equipped with displays of the radar data and selected channels of telemetered data and also with communication equipment. From this central location the operational characteristics of various onboard systems and subsystems — much more information than is available to the pilot — can be monitored to provide pilot backup monitoring and guidance information. Also, information can be transmitted regarding aircraft position, heading, velocity and altitude, angle of attack, acceleration, and a host of other quantities.

A photograph of the radar plotting board showing the trajectory and track for a representative flight and the range-capability footprints is presented in figure 23. In order to supply range-capability advice to the pilot as rapidly as possible, the range-footprint outlines shown in this figure were originally superimposed on the radar plotting-board maps used in the ground-controlling station. Thus, the ground controller, after ascertaining the vehicle's velocity and altitude, could determine which usable landing areas were within the vehicle's range capability at any particular instant. This technique is now being ground-mechanized with radar inputs of forward velocity, vertical velocity, and altitude into a computer which can provide a dynamic display of the range footprint, to a high-key altitude of 20,000 feet, as the flight progresses. The flight controller can then transmit the necessary information to the X-15 pilot.

USE OF ONBOARD AND GROUND-BASED GUIDANCE

As discussed in the preceding sections, a standard nose boom was used on the X-15 during the early part of the flight-envelope-expansion program up to $M \approx 3.3$. The boom provided values of angle of attack, angle of sideslip, airspeed, and pressure altitude to the pilot with sufficient accuracy. Piloting techniques were based on these parameters, and the resulting flight profiles were generally similar to those of previous research aircraft, such as the X-1 and X-2. After installation of the hypersonic flow-direction sensor to proceed to higher speeds and altitudes, the inertial platform was the primary source of velocity and altitude information to the pilot at the higher speeds. At the

lower speeds, the pitot probe ahead of the canopy and the fuselage static pressure provided the pilot with values of airspeed and altitude that were suitable for landing. The pilot's only source of angle-of-attack and angle-of-sideslip information was the flow-direction sensor. Because the reliability of this information from these two systems had not been adequately demonstrated to allow their use as prime instruments, normal acceleration and engine burning time were reverted to as the prime references during the post-launch roundout and powered portions of flight. Appreciable data have now been obtained with the inertial platform and ball-nose sensor to provide a basis for assessing the reliability of this information and also the attitude information provided by the inertial system. Because the current aircraft configuration and most of the flight program include the use of the ball-nose sensor, an alternate airspeed system, and the inertial data system, these sensors are discussed in the following sections.

The use of the cockpit display and ground-link information provided to the pilot can best be illustrated by describing typical phases of flight.

Pre-Launch Phase

Before each flight a preselected pitch angle, which is required for the climbout phase of that specific flight, is set on the three-axis attitude ball for pitch nulling by the pilot. Also, a preselected angle of attack, which is required for the most rigorous region of the flight (climbout, maneuvering, or entry regions, depending on the flight mission), is set for nulling on the three-axis-ball horizontal crossbar. During the B-52 taxi, takeoff, and climb operations, specific procedures are required to align the X-15 inertial system by using the B-52 carrier equipment, and to provide accurate initial conditions to the inertial system before the system is placed in the "inertial" mode for launch. Pre-launch operational procedures also include a comparison, by radio, of cockpit and ground-monitored, telemetered information pertaining to angle of attack and inertial attitude, velocity and height, and other significant quantities. In addition to these comparisons, the pre-launch checks also give the pilot and the ground-control monitors assurance that their instrumentation is operating satisfactorily. Except when alternate presentation information may be utilized or a specific display quantity may not be a prime guidance factor for the given flight, all primary flight quantities displayed to the pilot must be operating satisfactorily or the launch is cancelled. As a result of the developmental experience gained with the systems used in the X-15, flight cancellations because of system or display malfunction are rare.

Post-Launch Phase

Immediately after launch, the engine is ignited and the pilot increases the normal acceleration to, perhaps, 2g. He maintains this level to rotate the airplane to the preselected climbout pitch angle established by the mission requirements. Although the normal-acceleration indicator is the primary instrument used during this maneuver, a successful roundout can also be accomplished by using either the cockpit angle-of-attack or stabilizer-position indicator. The pitch null vernier on the side of the three-axis attitude ball is used for

precise acquisition and maintenance of the climbout pitch angle up to engine shutdown or until a push-over is prescribed by the flight mission. An illustration of the suitability of the display and piloting technique is shown in figure 24 in which the average pitch angle used during the powered climb is compared to the pitch angle specified for each flight mission. For the two appreciable discrepancies shown, the pilot realized that his pitch attitude differed from that planned because of unforeseen flight occurrences.

It must be emphasized that this control and use of the pitch-angle display has been satisfactory, despite appreciable longitudinal accelerations (nearly 4g) and the significant pitch attitudes utilized. These conditions, combined with pilot head motion, have occasionally given the pilot a feeling of near-vertigo or of rotating completely over on his back. Also, at the pitch angles required, the pilot cannot see the horizon and must rely on the attitude indicator to maintain proper heading and to keep wings level. Peak velocity attained along a given flight profile is dictated by engine operating time, assuming a constant throttle setting for the engine. Operating time is indicated by the stopwatch installed in the cockpit above the three-axis attitude ball. The inertial-platform-system indications of velocity and altitude provide additional cues to the pilot during most of the flight. Ground communications of elapsed time and of radar altitude and velocity also provide him with cues throughout the flight. The suitability of these techniques is shown by the comparison in figure 25 of the actual and planned peak velocities and altitudes attained during several flights.

High-Performance Phase

Generally, two different types of flight missions are flown with the X-15: an altitude profile in which very low values of dynamic pressure are attained, and a speed-mission profile involving appreciable values of dynamic pressure. In the altitude profile, climbout pitch attitude is maintained, using the pitch null vernier on the three-axis ball, until engine shutdown. After engine shutdown, the airplane is essentially in ballistic flight, and the prime cues used by the pilot for controlling are the attitudes from the three-axis ball and the nulling angle-of-attack and angle-of-sideslip crossbars which are also displayed on the same indicator. In this flight regime, all information is displayed centrally, thereby minimizing scanning and instrument cross-checks. For entry, the pilot tries to maintain a sideslip-nulled condition and attain a desired pitch attitude. This attitude is held until the dynamic-pressure buildup is sufficient to maintain a given angle of attack. (In the event of a malfunction in the ball-nose sensor or in the angle-of-attack indication, the entire entry can also be performed by using a given pitch attitude.) To maintain the desired angle of attack, the pilot uses the angle-of-attack indicator and the angle-of-attack nulling crossbar on the three-axis ball. He maintains this angle until the normal acceleration reaches a significant value, such as 5g, on the accelerometer gage. The remainder of the pullout to level flight is performed at this constant acceleration value using the accelerometer as the prime indicator.

A recent innovation in the cockpit display, for use during the ballistic-trajectory portion of altitude missions, employs a pilot-actuated switching

mechanism to present vernier heading on the vertical crossbars of the three-axis attitude indicator. During the ballistic ascent, the pilot maintains a sideslip-nulled condition on the vertical crossbar of the three-axis ball, switches this crossbar presentation to heading as the dynamic pressure becomes extremely low, and maneuvers the airplane as required at low dynamic pressure. He then nulls the heading presentation as dynamic pressure builds up in the descent, in order to attain zero angle of sideslip for the entry, and switches back to an angle-of-sideslip presentation on the vertical crossbar. In the single flight performed with this presentation, the display technique was judged to be satisfactory.

In the speed-mission profile, a push-over to a normal acceleration of $0g$ is effected after approximately one-half of the powered flight duration has been completed. The pilot maintains this acceleration on his cockpit acceleration gage until engine shutdown time is reached. In these missions, dynamic pressure and airplane skin temperatures are important because of operating and design limits; hence, careful observation of the dynamic-pressure indicator and of the inertial-velocity and altitude indicators is required. These quantities are cross-checked by ground communication of radar velocity and altitude. Since the speed missions are used basically to perform maneuvering stability or heat-transfer tests for research purposes, the pilot uses the angle-of-attack and sideslip indicators and the inertial-velocity and altitude indicators as prime cues while he is maneuvering in decelerating flight. In addition, for a specific maneuver during a given mission, the nulling crossbars on the three-axis ball are used for more accurate control of angle of attack and sideslip.

During the supersonic glide to the desired landing area, the accumulated effect of somewhat erroneous initial conditions supplied to the inertial system generally results in inaccurate indications of inertial altitude. However, the attitude indications and, to a lesser extent, the velocity indications are generally accurate for the entire flight. In this flight regime, the pilot's prime guidance cues have been the external cues he obtains by observing his position with respect to the landing area and by using cockpit indications of angle of attack for near-optimum lift-drag-ratio glide. Additional cues are provided by ground communication of airplane position and radar velocity and altitude.

Approach and Landing Phase

During the final phases of flight — the approach and landing — the pressure instruments that provide altitude, airspeed, and Mach number information to the pilot are utilized because of their reliable presentations at subsonic speeds. In setting up the approach pattern, the pilot uses his external cues of airplane position relative to the desired landing spot and his cockpit display of altitude and airspeed. A constant indicated airspeed of 300 knots is generally flown, with pattern adjustments for altitude changes. For optimum lift-drag ratio, a lower value of airspeed is used. For flare-initiation, external indications of altitude are used by the pilot. These altitudes have generally averaged less than 1,000 feet above the landing area. The flare point and velocity are selected so that the energy remaining after the flare allows sufficient time to make last-second adjustments in configuration and aircraft

attitude in order to execute the landing at acceptable values of angle of attack and sink rate and in proximity to the intended landing point. The pilots have generally landed within $\pm 1,000$ feet of the intended point and have touched down within ± 25 feet in two recent landings.

Escort-Aircraft Support

The importance of escort aircraft in checking the operation and well-being of the X-15 and its pilot and in supplying information to the airplane should be noted. Although several escort airplanes are deployed along specific portions of each planned flight track, they are most helpful in the launch and landing areas (including emergency landing areas). In the launch area, the escort aircraft checks the X-15 external configuration and reports on pre-launch operational procedures. During the landing maneuver at either a remote emergency site or in the designated X-15 landing area at Edwards Air Force Base, the escort aircraft verifies X-15 residual-fuel jettisoning, checks the X-15 configuration, verifies the X-15 indications of airspeed and altitude in the landing pattern, and informs the X-15 pilot of the height of the airplane above the ground as the touchdown is approached. Although X-15 landings have been successfully negotiated on one or two occasions when the escort airplane was not sufficiently close in the landing pattern to perform effectively, the use of the escort aircraft is considered mandatory because of the effective backup it provides.

CONCLUDING REMARKS

The X-15 flight program has been conducted with an expanding flight envelope to a Mach number of 6.04 and an altitude of 314,750 feet, using a combination of flight-guidance sensors, systems, and techniques, some of which were developed on the X-15 vehicle. Several of these systems appear to be satisfactory for providing research and pilot-display information relative to airspeed, altitude, dynamic pressure, flow-direction angles, and vehicle attitude. Other systems need additional refinement of calibration and some onboard computational equipment if required for the pilot display.

In general, use of a nose-boom installation on aircraft designed for speeds up to a Mach number of about 3 is recommended as the prime air-sensing source and for flow-direction measurements. For higher speeds and their associated altitudes, use of a ball nose or similar sensor having a high-temperature capability, in conjunction with an accurately calibrated static source which is independent of all configurational and rotational effects, appears to be warranted. The inertial system tested provided satisfactory attitude information for long periods; however, the accuracy of the altitude output deteriorated because of the short-term reliability of the system. A stagnation-temperature sensor appears to be a promising source for velocity information at supersonic and hypersonic speeds but requires further development.

Although the cockpit display used in the X-15 program can be improved, it has generally enabled precise attainment of goals for specific missions, particularly with the aid of special displays and backup methods devised in pre-flight simulation planning. Although the flight-guidance information provided to the pilot by ground-monitoring personnel is not essential for the accomplishment of every flight, it has contributed significantly to the success of the flight program.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., May 22, 1964.

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TABLE I

MEASUREMENT SPECIFICATIONS FOR INERTIAL FLIGHT-DATA SYSTEM

(Time duration: 300 sec)

Measurements required	Range	Accuracy, (rms)
Attitude angles, deg	Unlimited	0.5
Height, ft	0 to 500,000	5,000
Velocity:		
Total, ft/sec	7,000	70
Downrange, ft/sec	$\pm 7,000$	50
Crossrange, ft/sec	$\pm 3,000$	50
Vertical, ft/sec	$\pm 5,000$	20

X-15 AIRPLANE WITH NOSE BOOM

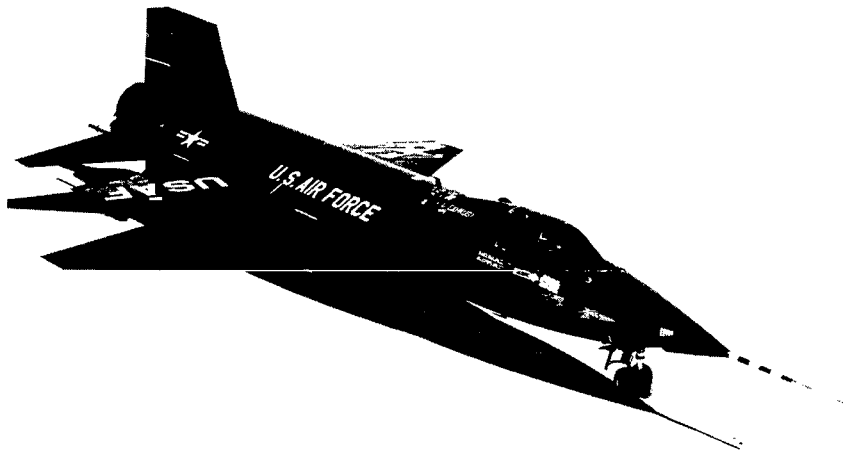
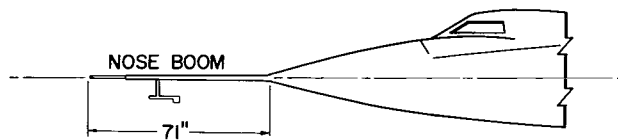


Figure 1

X-15 AIR-DATA INSTALLATIONS

NOSE-BOOM INSTALLATION



BALL-NOSE INSTALLATION

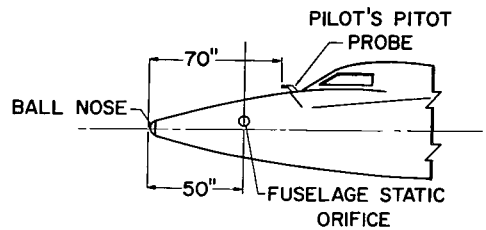


Figure 2

NOSE-BOOM PITOT-STATIC TUBE WITH FLOW-DIRECTION VANES

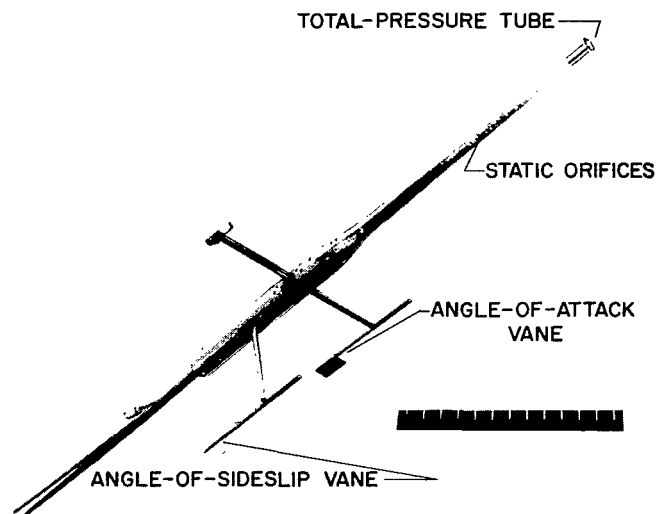


Figure 3

SEVERAL ALTERNATE PRESSURE SOURCES

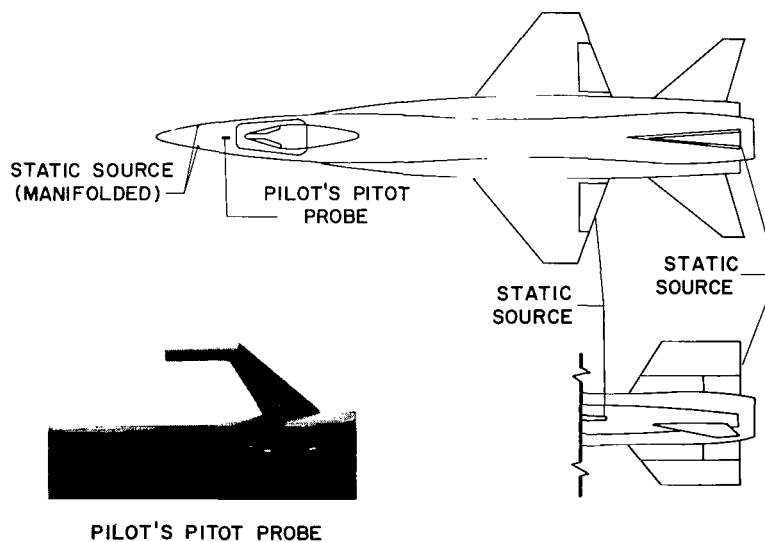


Figure 4

SUPERSONIC-HYPERSONIC FLOW-DIRECTION SENSOR

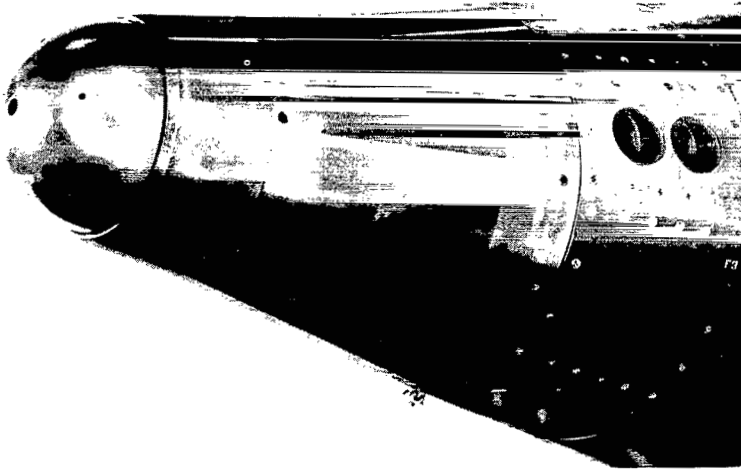


Figure 5

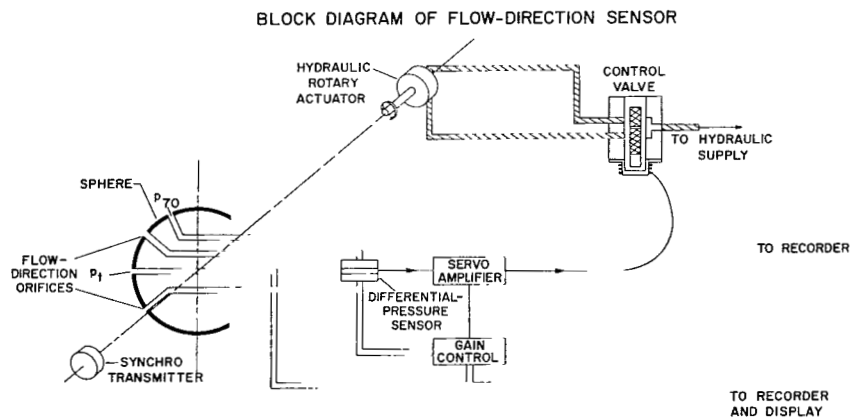


Figure 6

INTEGRATED INERTIAL FLIGHT DATA SYSTEM

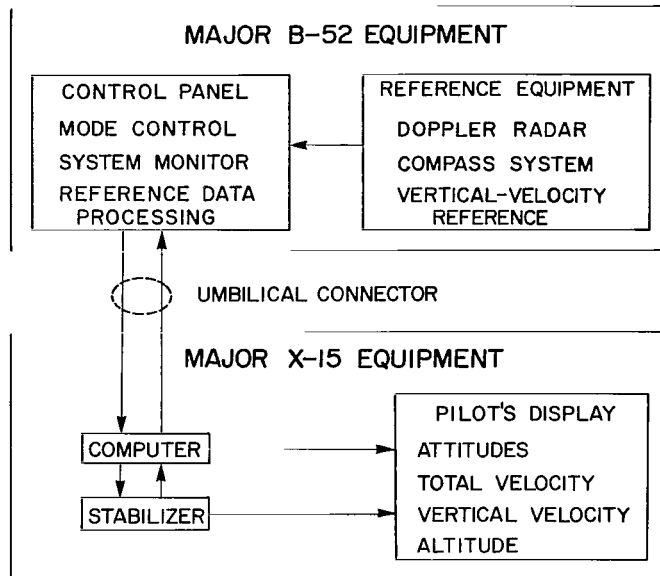


Figure 7

STAGNATION-TEMPERATURE PROBE

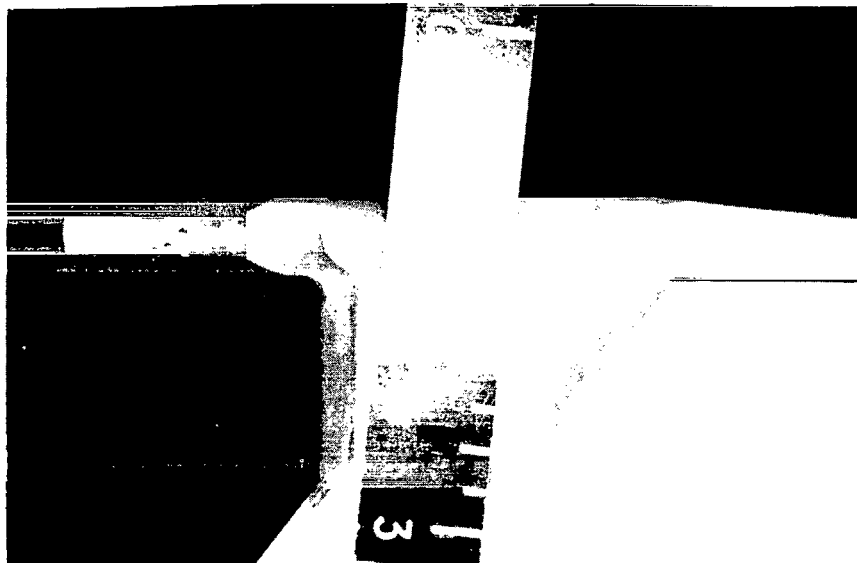


Figure 8

AIRSPEED-ALTITUDE SYSTEMS CALIBRATIONS

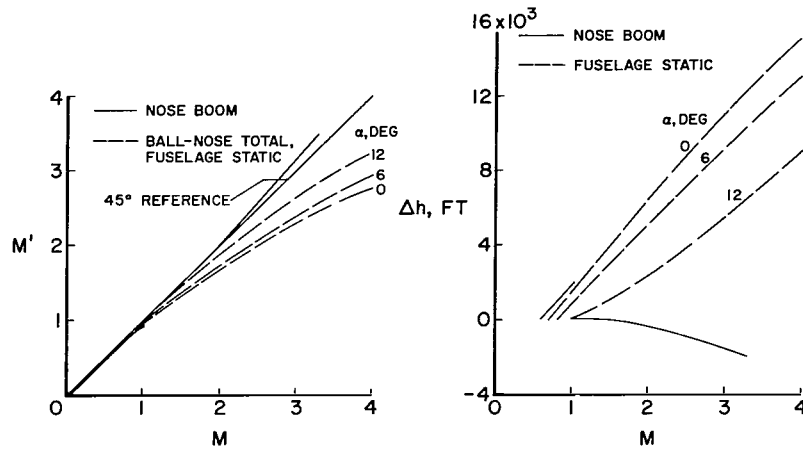


Figure 9

VARIATION OF TOTAL-PRESSURE RATIO FOR PILOT'S PITOT PROBE AND BALL NOSE

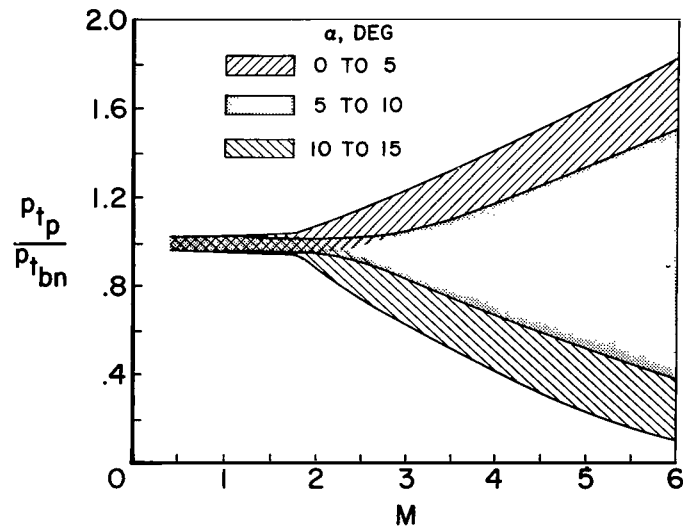


Figure 10

CALIBRATION OF BASE PRESSURE PORTS FOR USE AS STATIC SOURCES

SPEED BRAKES OPEN AND CLOSED

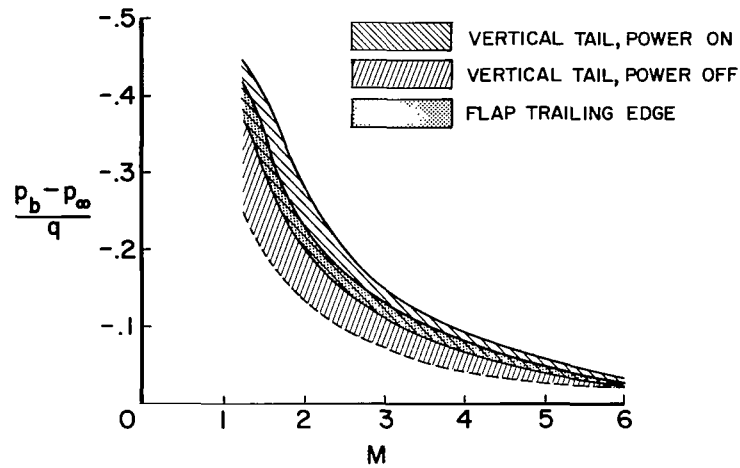


Figure 11

COMPARISON OF BALL-NOSE ALTERNATE STATIC SOURCE — TOTAL-PRESSURE SYSTEM WITH NOSE-BOOM SYSTEM

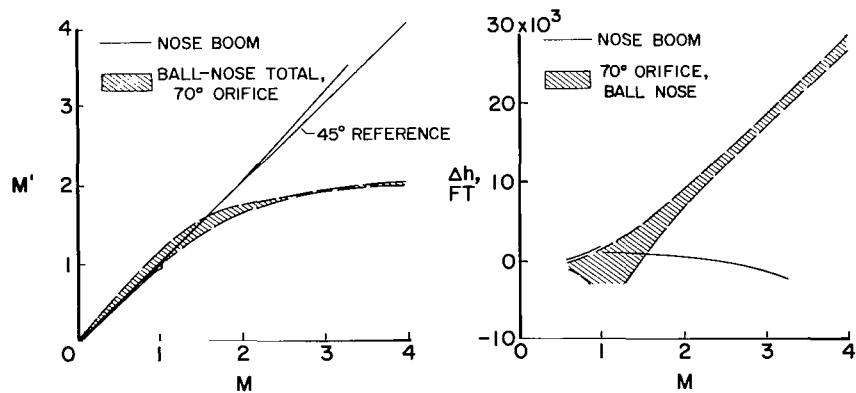


Figure 12

CHARACTERISTICS OF INERTIAL FLIGHT-DATA SYSTEM

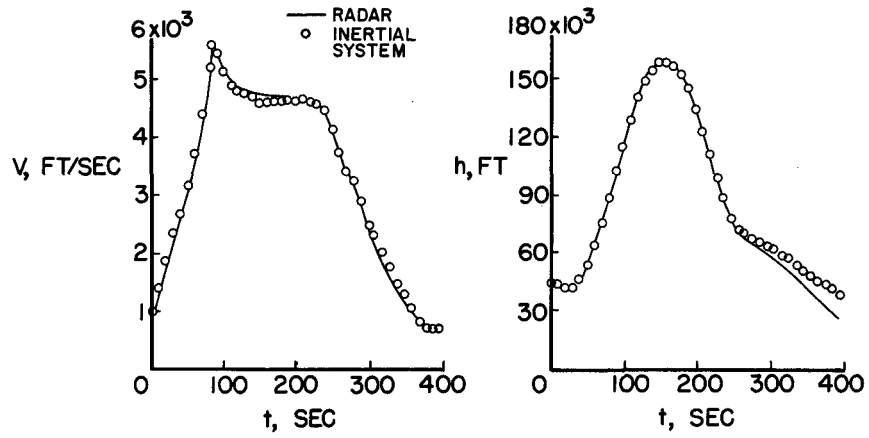


Figure 13

CHARACTERISTICS OF STAGNATION-TEMPERATURE VELOCITY SENSOR

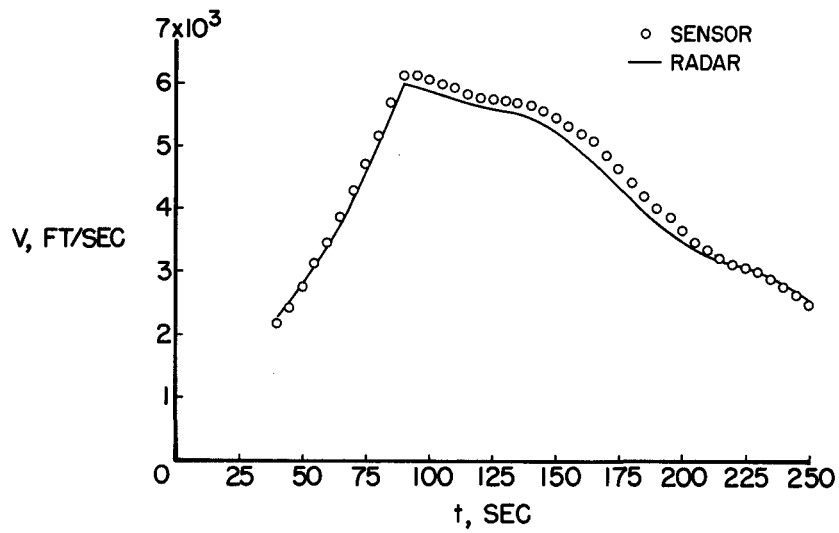


Figure 14

CHARACTERISTICS OF VANE-BOOM AND BALL-NOSE FLOW-DIRECTION SENSORS

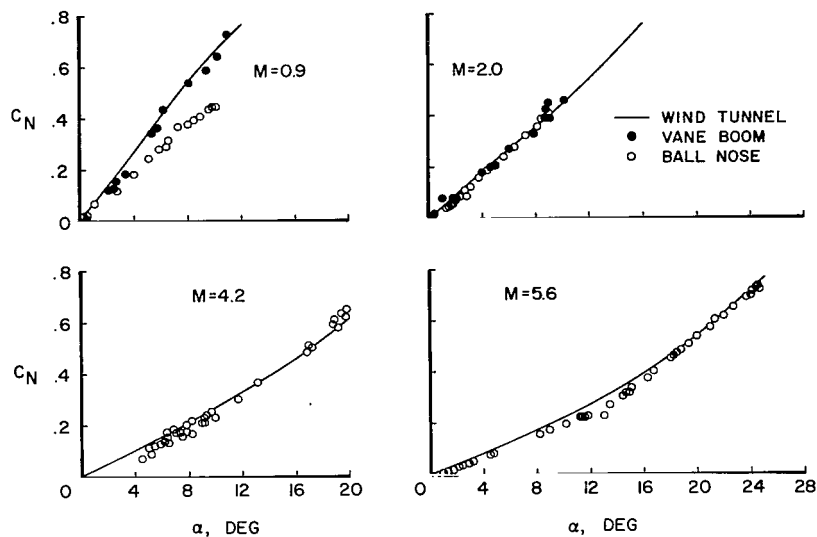


Figure 15

ACCURACY OF BALL-NOSE FLOW-DIRECTION SENSOR AT LOW DYNAMIC PRESSURE

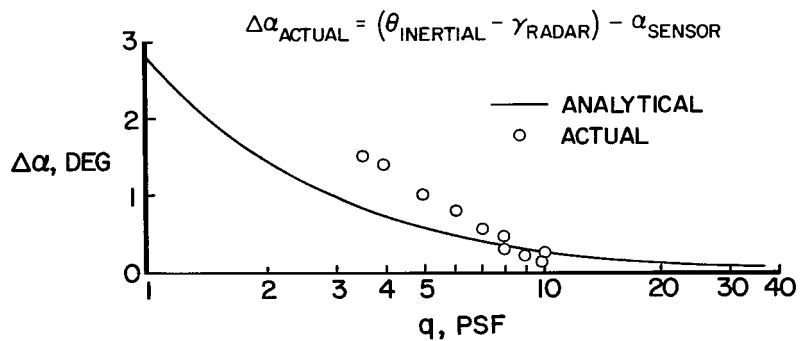


Figure 16

COMPARISON OF PITCH-ATTITUDE MEASUREMENTS AT ENGINE BURNOUT

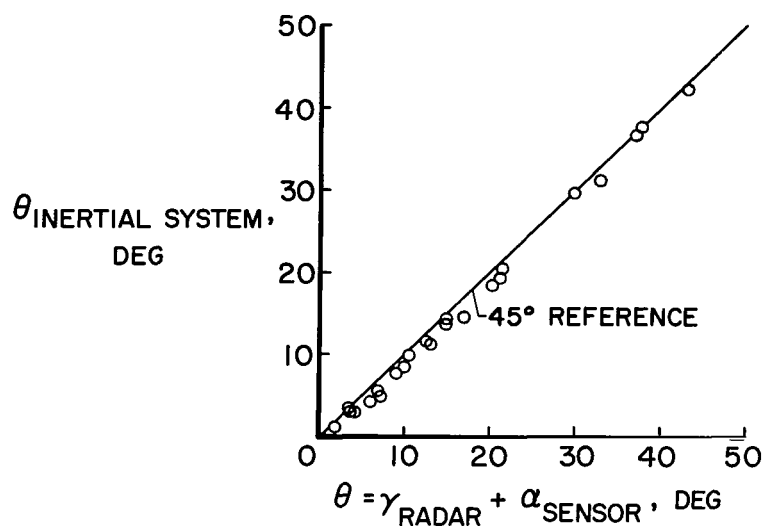


Figure 17

X-15 DISPLAY PANEL

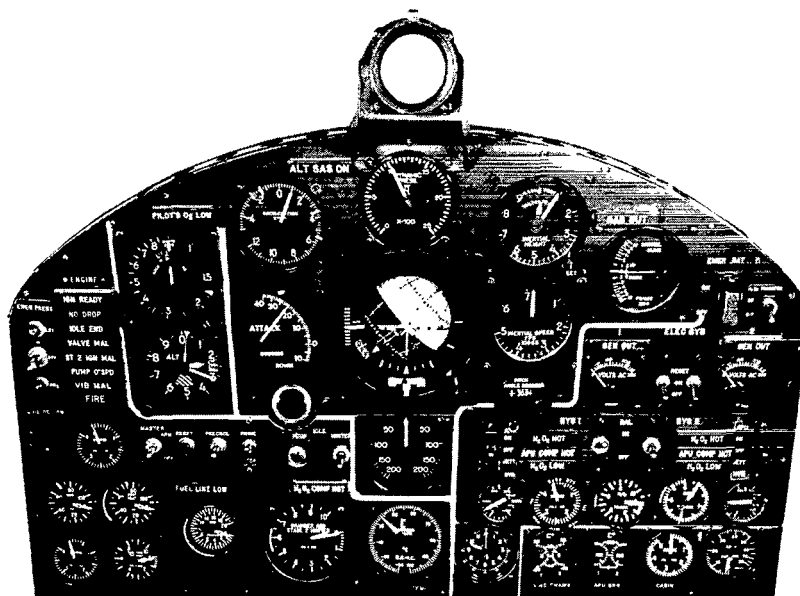


Figure 18

X-15 THREE-AXIS ATTITUDE BALL

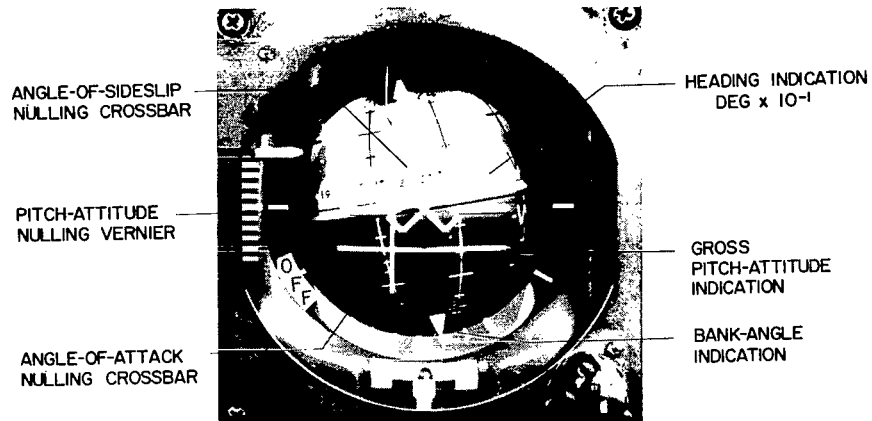


Figure 19

DYNAMIC-PRESSURE VARIATION BASED ON BALL-NOSE TOTAL PRESSURE ANALYTICAL VARIATION

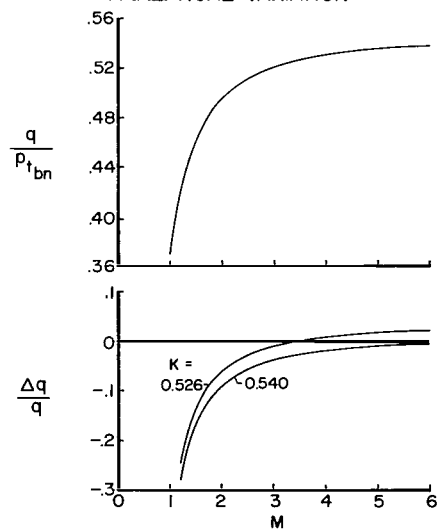


Figure 20

DYNAMIC-PRESSURE VARIATION BASED ON BALL-NOSE TOTAL PRESSURE

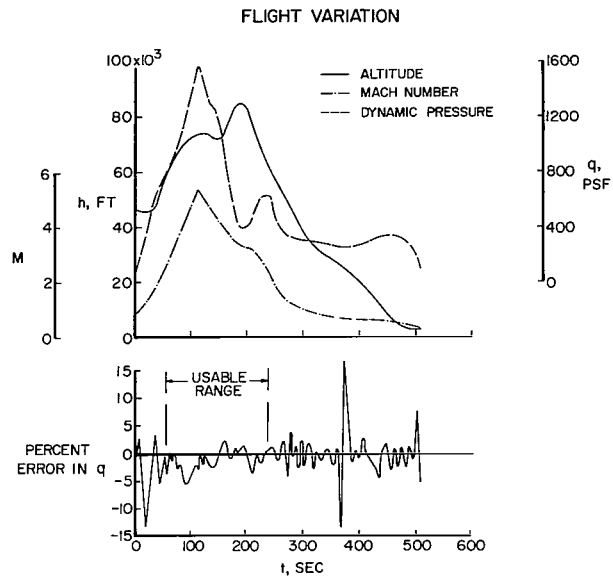


Figure 21

X-15 GROUND-CONTROL STATION AT FRC

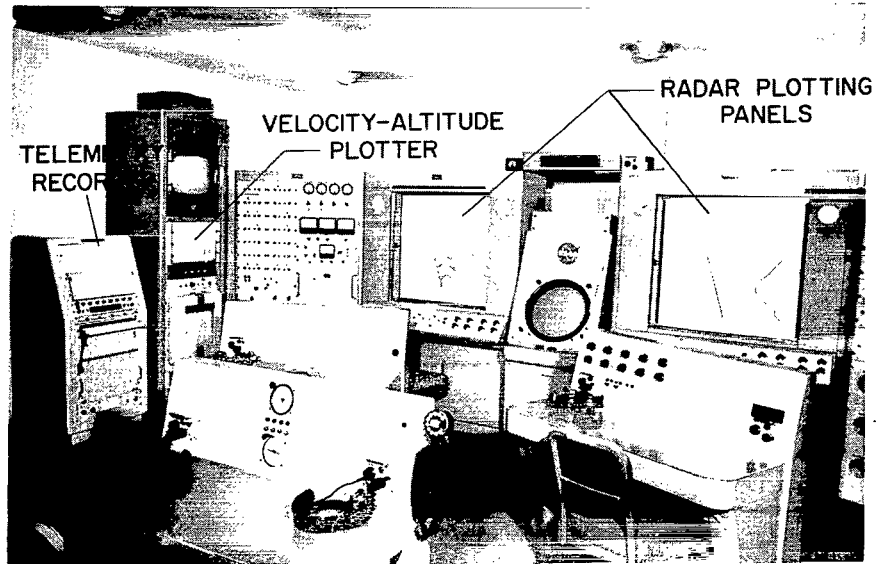


Figure 22

FRC RADAR PLOTTING-BOARD MAP

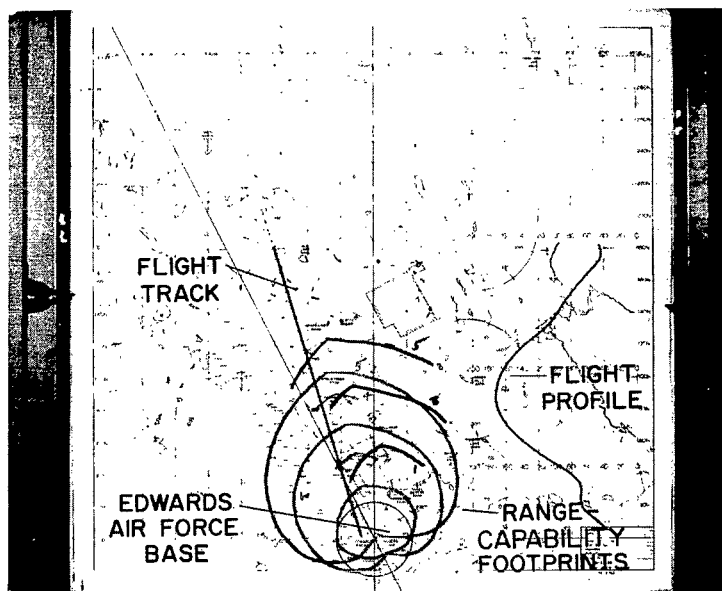


Figure 23

COMPARISON OF ACTUAL AND PLANNED PITCH ATTITUDE FOR X-15 FLIGHTS

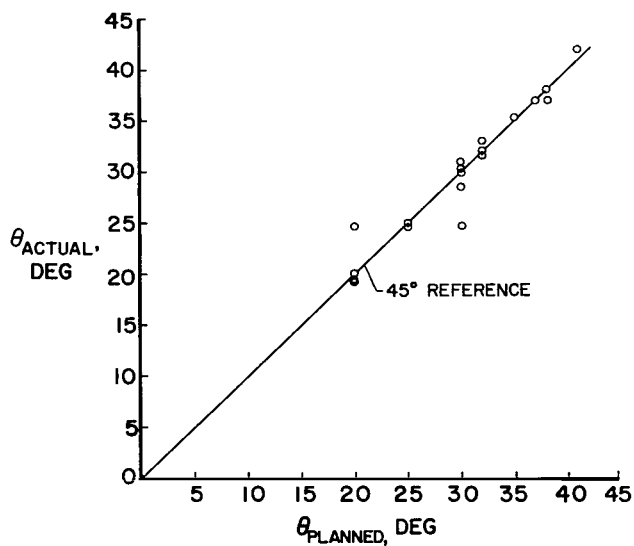


Figure 24

COMPARISON OF ACTUAL AND PLANNED PEAK PERFORMANCE FOR X-15 FLIGHTS

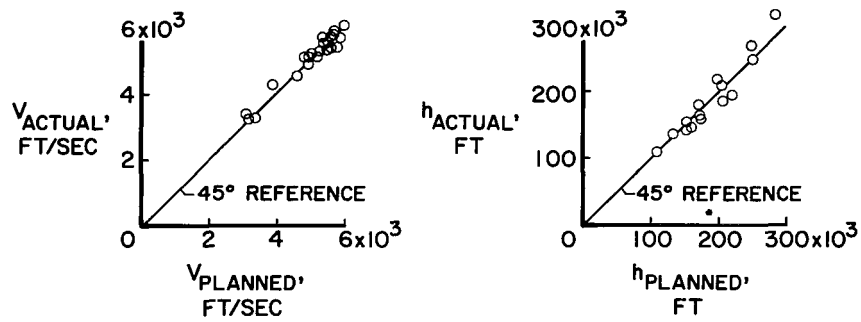


Figure 25

2/7/85
8

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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